Solar Neutrinos: A Scientific Puzzle

John N. Bahcall and Raymond Davis, Jr.

For the past 15 years we have tried, in collaboration with many colleagues in astronomy, chemistry, and physics, to understand and test the theory of how the sun produces its radiant energy (observed on the earth as sunlight). All of us have been surprised by the results: there is a large, unexplained disagreement between observation and the supposedly well established theory. This discrepancy has led to a crisis in the theory of stellar evolution; many authors are openly questioning some of the basic principles and approximations in this supposedly dry (and solved) subject.

One may well ask, Why devote so much effort in trying to understand a backyard problem like the sun's thermonuclear furnace when there are so many exciting and exotic discoveries occurring in astronomy? Most natural scientists believe that we understand the process by which the sun's heat is produced—that is, in thermonuclear reactions that fuse light elements into heavier ones, thus converting mass into energy. However, no one has found an easy way to test the extent of our understanding because the sun's thermonuclear furnace is deep in the interior, where it is hidden by an enormous mass of cooler material. Hence conventional astronomical instruments can only record the photons emitted by the outermost layers of the sun (and other stars). The theory of solar energy generation is sufficiently important to the general understanding of stellar evolution that one would like to find a more definitive test.

There is a way to directly and quantitatively test the theory of nuclear energy generation in stars like the sun. Of the particles released by the assumed thermonuclear reactions in the solar interior, only one has the ability to penetrate from the center of the sun to the surface and escape into space: the neutrino. Thus neutrinos offer us a unique possibility of "looking" into the solar interior. Moreover, the theory of stellar aging by thermonuclear burning is widely used in interpreting many kinds of astronomical information and is a necessary link in establishing such basic data as the ages of the stars and the abundances of the elements. The parameters of the sun (its age, mass, luminosity, and chemical composition) are better known than those of any other star, and it is in the simplest and best understood stage of stellar evolution, the quiescent main sequence stage. Thus an experiment designed to capture neutrinos produced by solar thermonuclear reactions is a crucial one for the theory of stellar evolution. We also hoped originally that the application of a new observing technique would provide added insight and detailed information. It is for all of these reasons (a unique opportunity to see inside a star, a well-posed prediction of a widely used theory, and the hope for new insights) that so much effort has been devoted to the solar neutrino problem.

Nuclear Fusion in the Sun

We shall now outline briefly the conventional wisdom (*1*) regarding nuclear fusion as the energy source for main sequence stars like the sun. It is assumed that the sun shines because of fusion reactions similar to those envisioned for terrestrial fusion reactors. The basic solar process is the fusion of four protons to form an alpha particle, two positrons (e^+), and two neutrinos (ν); that is, $4p \rightarrow \alpha + 2e^+ + 2\nu$. The principal reactions are shown in Table 1 with a column indicating in what percentage of the solar terminations of the proton-proton chain each reaction occurs. The rate for the initiating proton-proton (PP) reaction, number 1 in Table 1, is largely determined by the total luminosity of the sun. Unfortunately, these neutrinos are below the threshold, which is 0.81 Mev, for the ^{37}Cl experiment that has been performed to detect solar neutrinos (*2*). The PEP reaction (number 2), which is the same as the familiar PP reaction except for having the electron in the initial state, is detectable in the ^{37}Cl experiment. The ratio of PEP to PP neutrinos is approximately independent of which model (see below) one uses for the solar properties (*3*). Two other reactions in Table 1 are of special interest. The capture of electrons by ^{7}Be (reaction 6) produces detectable neutrinos in the ^{37}Cl experiment. The ^{8}B beta decay, reaction 9, was expected (*4*) to be the main source of neutrinos for the ^{37}Cl experiment because of their relatively high energy (14 Mev), although it is a rare reaction in the sun (see Table 1). There are also some less important neutrino-producing reactions from the carbon-nitrogen-oxygen (CNO) cycle, but we shall not discuss them in detail since the CNO cycle is believed to play a rather small role in the energy-production budget of the sun.

In order to calculate how often the various nuclear reactions occur, one must make a detailed model of the interior of the sun. The techniques for constructing such models are standard (*1, 5*) (although greater precision is required for the solar neutrino problem than for most other problems in stellar evolution). The physics involved is elementary. One imposes at each point in the star the condition of hydrostatic equilibrium; that is, the condition that the pressure gradient balances the gravitational attraction. Both radiative and kinetic contributions to the pressure are included. The energy generation is given by an integral over the derived temperature-density distribution, using the calculated rates of all the nuclear reactions. Energy transport in the solar interior is largely by radiation and hence depends inversely on the radiative opacity. It is conventional to assume a primordial chemical composition that is homogeneous throughout the sun and equal to the presently observed surface chemical composition. One makes a sequence of successive solar models, requiring that the calculated luminosity equal the observed solar luminosity at a model age of 4.7 × 10^9 years, the age of the solar system.

Brookhaven Solar Neutrino Experiment

Neutrinos can be captured in nuclei by a reaction called the inverse beta process, so called because it is the inverse of the beta decay process in which neutrinos are created. The Brookhaven solar neutrino detector is based on the neutrino capture reaction (*2, 6*)

$$\nu + {}^{37}\mathrm{Cl} \underset{\text{decay}}{\overset{\text{capture}}{\rightleftarrows}} {}^{37}\mathrm{Ar} + e^-$$

which is the inverse of the electron capture decay of ^{37}Ar. The radioactive decay occurs with a half-life of 35 days. This reaction was chosen for the Brookhaven solar

---

John Bahcall is professor of natural science at the Institute for Advanced Study, Princeton, New Jersey 08540, and Raymond Davis is senior chemist at Brookhaven National Laboratory, Upton, Long Island, New York 11973.

neutrino experiment because of its unique combination of physical and chemical characteristics, which were favorable for building a large-scale solar neutrino detector. Neutrino capture to form ^{37}Ar in the ground state has a relatively low energy threshold (0.81 Mev) and a favorable cross section, nuclear properties that are important for observing neutrinos from ^{7}Be, ^{13}N, and ^{15}O decay and the PEP reaction. If neutrinos are energetic enough, ^{37}Ar can be formed in one of its many excited states (*4, 7*). Neutrinos from ^{8}B decay have sufficient energy to feed these excited states and have a much higher capture cross section than those from the lower energy neutrino sources mentioned above. Because of this, the capture rate was expected to be due primarily to the ^{8}B neutrinos. The nuclear properties of ^{37}Ar, ^{37}K, and ^{37}Ca have been determined in various laboratory measurements, providing a solid experimental basis for the original theoretical calculations of the neutrino capture cross section of ^{37}Cl (*7*). The sensitivity of the detector for neutrinos from the various solar processes depends on these calculated cross sections.

The ^{37}Cl reaction is very favorable from a chemical point of view (*2, 6, 8*). Chlorine is abundant and inexpensive enough that one can afford the many hundreds of tons needed to observe solar neutrinos. The most suitable chemical compound is perchloroethylene, C_2Cl_4, a pure liquid, which is manufactured on a large scale for cleaning clothes. The product, ^{37}Ar, is a noble gas, which should ultimately exist in the liquid as dissolved atoms. The neutrino capture process produces an ^{37}Ar atom with sufficient recoil energy to break free of the parent perchloroethylene molecule and penetrate the surrounding liquid, where it reaches thermal equilibrium. Initially the recoiling argon atom is ionized. As it slows down, it will extract electrons from a neighboring molecule and become a neutral argon atom. A neutral argon atom behaves as dissolved argon, which can be removed easily from the liquid by purging with helium gas. These chemical processes are of crucial importance to the operation of the detector.

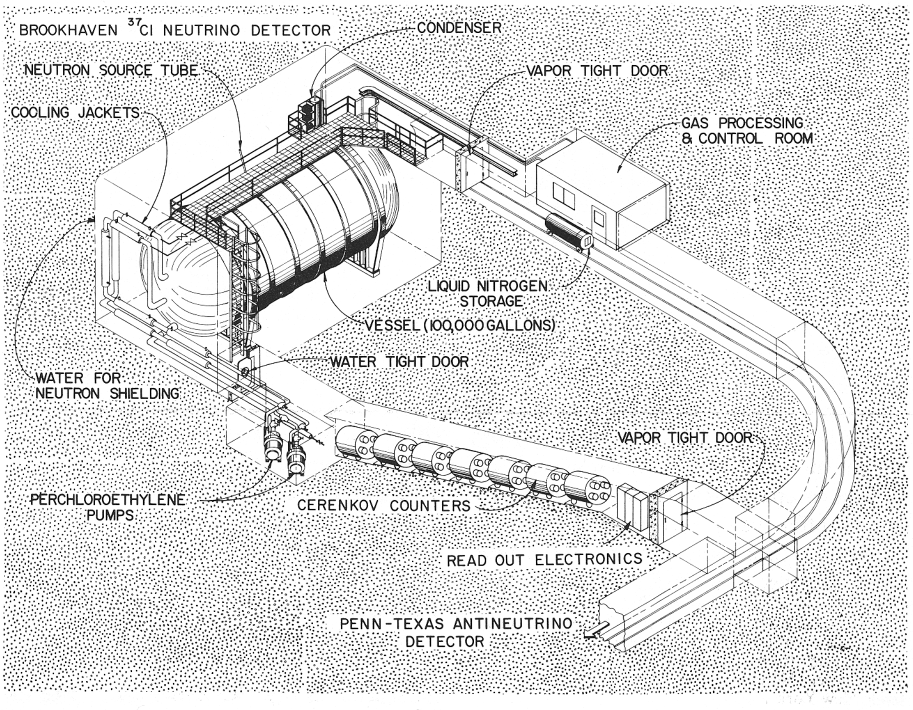
The Brookhaven ^{37}Cl detector (see Fig. 1) was built deep underground to avoid the production of ^{37}Ar in the detector by cosmic rays. This was done with the cooperation of the Homestake Gold Mining Company (Lead, South Dakota), who excavated a large cavity in their mine (~1500 m below the surface) to house the experiment. The final detector system consists of an ~ 400,000-liter tank of perchloroethylene, a pair of pumps to circulate helium through the liquid, and a small building to house the extraction equipment, as shown in Fig. 1.

The chemical processing is relatively simple (*2, 8*). A small amount of isotopically pure ^{36}Ar (or ^{38}Ar) carrier gas is placed in the tank and stirred into the liquid to insure that it dissolves. The tank is then allowed to stand about 100 days, permitting the ^{37}Ar activity to grow to nearly the saturation value. After this period the pumps are turned on, circulating helium through the tank. Helium from the tank passes through a chemical extraction system consisting sequentially of a condenser, an absorber for perchloroethylene vapor, and a charcoal trap at liquid nitrogen temperature, which collects the argon gas. The gas is removed from the charcoal absorber, purified, and placed in a miniature proportional counter to observe ^{37}Ar decay events. Recovery of argon from the tank is very high, at least 90 percent, and is determined in each experiment by measuring the amount of ^{36}Ar recovered compared to the amount introduced initially. If the standard solar model were correct, one would expect about 50 ^{37}Ar atoms in the 400,000 liters of liquid at the time it is purged. These few atoms of ^{37}Ar behave chemically in the same way as the 3×10^{19} atoms of ^{36}Ar introduced as a carrier gas. Therefore, a direct determination of the ^{36}Ar recovered is a reliable measure of the ^{37}Ar atom recovery.

Two additional tests have been performed to ensure that ^{37}Ar produced in the large tank is indeed recovered efficiently. In one, a small neutron source was placed in the center of the tank through a reentrant tube. Neutrons produce ^{37}Ar in the liquid by a series of nuclear reactions, and one verifies that the ^{37}Ar is recovered along with the carrier gas. The second test was to introduce a measured number of ^{37}Ar

Table 1. The proton-proton chain in the sun.

Number	Reaction	Solar terminations (%)	Maximum neutrino energy (Mev)
1	$p + p \rightarrow {}^{2}H + e^{+} + \nu$	99.75	0.420
	or		
2	$p + e^{-} + p \rightarrow {}^{2}H + \nu$	0.25	1.44 (monoenergetic)
3	${}^{2}H + p \rightarrow {}^{3}He + \gamma$		
4	${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$	86	
	or		
5	${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$		
6	${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu$		0.861 (90%), 0.383 (10%) (both monoenergetic)
7	${}^{7}Li + p \rightarrow 2\,{}^{4}He$	14	
	or		
8	${}^{7}Be + p \rightarrow {}^{8}B + \gamma$		
9	${}^{8}B \rightarrow {}^{8}Be^{*} + e^{+} + \nu$		14.06
10	${}^{8}Be^{*} \rightarrow 2\,{}^{4}He$	0.02	



atoms (500) into the detector and then remove them, measuring the overall recovery and counting efficiency. Both of these tests show that ^{37}Ar is efficiently removed by the procedures used.

The entire gas sample from the tank is placed in a small proportional counter with an internal volume of less than a cubic centimeter. The decay of ^{37}Ar is characterized by the energy deposited in the counter by the Auger electrons following the electron capture process. These Auger electrons have a very short range in the counter and produce a characteristic pulse shape, which can be distinguished electronically. In a typical experiment only about two to four events are observed in the counter that have the proper characteristics for an ^{37}Ar decay.

We might add that Jacobs (*9*) has raised the question of whether the chemical tests are valid, and has suggested that ^{37}Ar produced by neutrino capture either does not become a neutral dissolved argon atom or that once formed it is trapped in a molecular cage or compound. The possible formation of an argon molecule ion with perchloroethylene was tested by an experiment of Leventhal and Friedman (*10*), and they showed that the charge exchange process is at least 100 times more likely. The formation of molecular cages or rare gas compounds in perchloroethylene is very unlikely. Even if they were formed, an argon atom would not be retained, as evidenced by the diffusion of rare gases in plastics. One could test the chemical fate of argon (*11*) by studying the formation of ^{36}Ar from molecules of ^{36}Cl-labeled perchloroethylene, $C_2Cl_3{}^{36}Cl$. The recoil dynamics and ultimate chemical behavior of the resulting ^{36}Ar ion produced in the beta decay of ^{36}Cl (half-life, 308,000 years) are identical to those of the neutrino capture process. Because of the intense ^{36}Cl source needed, this experiment is not an easy one to perform, but it is now being undertaken. There is little question about the chemical fate of ^{37}Ar produced by neutrino capture, and we feel certain that recovery of ^{37}Ar from the 400,000-liter detector is accurately measured by the ^{36}Ar (or ^{38}Ar) recovery measurements described above.

Table 2. Significance of counting rates in the ^{37}Cl experiment. One solar neutrino unit (SNU) = 10^{-36} captures per target particle per second.

Counting rate (SNU)	Significance of counting rate
35	Expected if the CNO cycle produces the solar luminosity
~6 ± 2	Predictions of current models
1.5	Expected as a lower limit consistent with standard ideas of stellar evolution
0.3	Expected from the PEP reaction, hence a test of the basic idea of nuclear fusion as the energy source for main sequence stars

Observational Results

A set of ten experimental runs carried out in the Brookhaven ^{37}Cl experiment over the last 3 years show that the ^{37}Ar production rate in the tank is 0.13 ± 0.13 ^{37}Ar atoms per day (*12*). Even though the tank is nearly a mile underground, a small amount of ^{37}Ar is produced by cosmic rays. An evaluation of data obtained by exposing 7500 liters of C_2Cl_4 at various depths underground indicates that the cosmic-ray production rate in the detector is 0.09 ± 0.03 ^{37}Ar atoms per day (*13*). Thus, the observed rate in the detector is essentially the same as the extrapolated cosmic-ray background, and there is no evidence (at the 90 percent confidence level) for a solar neutrino capture rate of 1.5 solar neutrino units (SNU; 1 SNU = 10^{-36} captures per target particle per second). The individual experiments and the average rate are illustrated in Fig. 2, including some more recent runs.

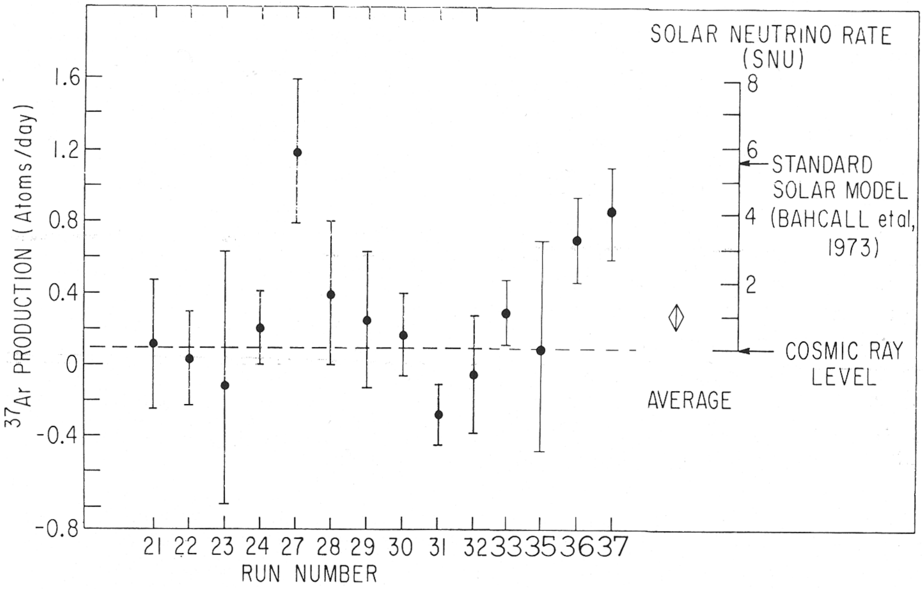


Fig. 2. Summary of the neutrino observations.

Even though the average ^{37}Ar production rate shown in Fig. 2 is very low, there are occasional high runs. These may be due to statistical fluctuations in the data or to rare cosmic-ray events. It is unlikely that variations on the time scale of months are due to changes in the solar neutrino flux, since solar thermal time scales are tens of thousands of years or longer.

Is there any hope of improving the sensitivity of the present ^{37}Cl detector? There are two limitations: the background counting rate of the counters used to measure the ^{37}Ar activity, and the cosmic-ray background effect. Attempts are being made to decrease the counter background, which is at present 1 to 2 counts per month, to less than 0.5 per month. With this improvement a search could be made for a solar neutrino flux in the range of 0.5 to 1 SNU.

The ^{37}Cl experiment tests theoretical ideas at different levels of meaning, depending on the counting rate being discussed. The various counting rates and their significance are summarized in Table 2. It is obvious from a comparison of Table 2 with the experimental results given above (and in Fig. 2) that the value (*7*) of 35 SNU's based on the CNO cycle is ruled out. More surprisingly, the best current models (*14*) based on standard theory, which imply ~ 5.5 SNU's, are also inconsistent with the observations. This disagreement between standard theory and observation has led to many speculative suggestions of what might be wrong. One such suggestion (*15*), that in the solar interior the heavy element abundance is at least a factor of 10 less than the observed surface abundance, leads to an expected counting rate of 1.5 SNU's (see Table 2), which is about as low a prediction as one can obtain from solar models without seriously changing current ideas about the physics of the solar interior. We note that present and future versions of the ^{37}Cl experiment are not likely to reach a sensitivity as low as 0.3 SNU, the minimum counting rate (from reaction 2 of Table 1) that can be expected if the basic idea of nuclear fusion as the energy source for main sequence stars is correct.

Speculations

The conflict between observation and standard theory has led to many speculations about the solar interior that were advanced because their proponents believed that the subject is in a state of crisis. For example, it has been suggested that the sun contains a black hole in its center, which is currently supplying more than half the observed solar luminosity through energy radiated when the black hole accretes mass from the surrounding gas (*16*). It has also been suggested that the sun is in a transient phase during which the interior luminosity produced by nuclear reactions is much less than the observed luminosity, which results from photons slowly diffusing out from the interior to the surface (*17*). These suggestions have not been widely accepted because they require the sun to be in a special state during the ^{37}Cl neutrino observations and also because there is no evidence from theoretical calculations that the dynamical behavior of the sun would be as required by these speculations. Other radical ad hoc assumptions about the solar interior that have recently been put forward include a departure from the Maxwellian velocity distribution at energies large compared to the thermal energy (*18*), the existence of very large central magnetic fields in the solar interior (*19*), and a critical temperature below which hydrogen and helium are immiscible (*20*). One imaginative cosmologist has even suggested that the exterior half of the sun's mass was added, with an entirely different composition from the interior half, about 5 billion years ago (*21*).

In addition to the many speculations about radical changes in the theory of stellar evolution, it has also been suggested (*22*) that the neutrino may behave differently in traversing astronomical distances (10^{13} cm) than has been inferred from laboratory measurements over distances of less than 10^{3} cm. It has been proposed (*23*) that the neutrino has a tiny rest mass and decays into a (presently unknown) lower mass boson. The latter suggestion has not been taken very seriously by most physicists because there is no independent evidence for the postulated decay product and because weak interaction theory has a more elegant structure if neutrinos have zero rest mass.

The attitude of many physicists toward the present discrepancy is that astronomers never really understand astronomical systems as well as they think they do, and the failure of the standard theory in this simple case just proves that physicists are correct in being skeptical of the astronomers' claims. Many astronomers believe, on the other hand, that the present conflict between theory and observation is so large and elementary that it must be due to an error in the basic physics, not in our astrophysical understanding of stellar evolution.

The Next Experiment

Another experiment is required to settle the issue of whether our astronomy or our physics is at fault. Fortunately, one can make a testable distinction. The flux of low energy neutrinos from the PP and PEP reactions (numbers 1 and 2 in Table 1) is almost entirely independent of astronomical uncertainties and can be calculated from the observed solar luminosity, provided only that the basic physical ideas of nuclear fusion as the energy source for the sun and of stable neutrinos are correct. If these low energy solar neutrinos are detected in a future experiment, we will know that the present crisis is caused by a lack of astronomical understanding. If the low energy neutrinos are shown not to reach the earth, then even many physicists would be inclined to suspect their physics.

The radiochemical approach, even with its inherent backgrounds and indiscriminate signal, appears to be the only method with sufficient sensitivity to make possible another solar neutrino experiment. If one examines all possible inverse beta processes with low threshold energies, satisfactory neutrino capture cross sections, and suitable product lifetimes, and also considers the availability of the target element and the ease of separation of the target, only one reasonably good candidate has been found capable of observing the abundant flux of PP neutrinos. This reaction is the capture of neutrinos by ^{71}Ga to produce ^{71}Ge, an isotope with an 11-day half-life. The threshold, 233 kev, is ideal for observing neutrinos from the PP reaction. Gallium is very expensive and is now used for making light-emitting diodes for minicomputer readout displays. About 20 tons of gallium are needed for a solar neutrino detector.

Another approach is to use the capture of neutrinos by ^{7}Li to form ^{7}Be, an isotope with a 53-day half-life. Although this reaction has a high threshold, 861 kev, the target, ^{7}Li, has a neutrino capture cross section for PEP neutrinos 34 times higher than that of ^{37}Cl, and the reaction is favorable for observing PEP neutrinos. The neutrino capture cross sections for this target are accurately known (*1*) and could, in principle, permit one to determine the relative frequency of capture of neutrinos from the various reactions listed in Table 1. Development work has started on chemical separation methods and counting techniques. The experiment might involve about 200,000 liters of nearly saturated aqueous lithium chloride solution, from which about 30 atoms of ^{7}Be must be separated. Needless to say, such an experiment is not easy.

References and Notes

1. J. N. Bahcall and R. L. Sears, *Annu. Rev. Astron. Astrophys.* **10**, 25 (1972).
2. R. Davis, Jr., *Phys. Rev. Lett.* **12**, 303 (1964); *Proc. Int. Conf. Neutrino Phys. Astrophys. (Moscow)* **2**, 99 (1969).
3. J. N. Bahcall, N. A. Bahcall, G. Shaviv, *Phys. Rev. Lett.* **20**, 1209 (1968).
4. J. N. Bahcall, *ibid.* **22**, 300 (1969).
5. M. Schwarzschild, *Structure and Evolution of the Stars* (Princeton Univ. Press, Princeton, N.J., 1958).
6. B. Pontecorvo, *Chalk River Lab. Rep. PD-205* (1946); L. W. Alvarez, *Univ. Calif. Radiat. Lab. Rep. UCRL-328* (1949).
7. J. N. Bahcall, *Phys. Rev. Lett.* **17**, 398 (1966).
8. R. Davis, Jr., D. C. Harmer, F. H. Neely, in *Quasars and High-Energy Astronomy*, K. N. Douglas *et al.*, Eds. (Gordon & Breach, New York, 1969), p. 287.
9. K. C. Jacobs, *Nature (London)* **256**, 560 (1975).
10. J. J. Leventhal and L. Friedman, *Phys. Rev. D* **6**, 3338 (1972).
11. F. Reines and V. Trimble, Eds. *Proceedings of the Solar Neutrino Conference* (University of California, Irvine, 1972); V. Trimble and F. Reines, *Rev. Mod. Phys.* **45**, 1 (1973).
12. R. Davis, Jr., and J. M. Evans, *Proc. 13th Int. Cosmic Ray Conf.* **3**, 2001 (1973).
13. A. W. Wolfendale, E. C. M. Young, R. Davis, *Nature (London) Phys. Sci.* **238**, 130 (1972).
14. J. N. Bahcall *et al., Astrophys. J.* **184**, 1 (1973).
15. J. N. Bahcall and R. K. Ulrich, *ibid.* **170**, 593 (1971).
16. M. J. Newman, D. D. Clayton, R. J. Talbot, *ibid.*, in press.
17. E. E. Salpeter, *Comments Nucl. Part. Phys.* **2**, 97 (1968); W. A. Fowler, *Colloquium on Cosmic Ray Studies in Relation to Recent Developments in Astronomy and Astrophysics* (Tata Institute of Fundamental Research, Bombay, 1968), p. 245; W. R. Sheldon, *Nature (London)* **221**, 650 (1969); F. W. W. Dilke and D. O. Gough, *ibid.* **240**, 262 (1972); W. A. Fowler, *ibid.* **238**, 24 (1972).
18. D. D. Clayton, E. Dwek, M. J. Newman, J. Talbot, *Astrophys. J.* **199**, 494 (1975).
19. D. Bartenwerfer, *Astron. Astrophys.* **25**, 455 (1973); S. M. Chitre, D. Ezer, R. Stothers, *Astrophys. Lett.* **14**, 37 (1973).
20. J. C. Wheeler and A. G. W. Cameron, *Astrophys. J.* **196**, 601 (1975).
21. F. Hoyle, *Astrophys. J. Lett.* **197**, L127 (1975).
22. B. Pontecorvo, *Sov. Phys. JETP* **26**, 984 (1964); V. Gribov and B. Pontecorvo, *Phys. Lett.* **28B**, 493 (1969); J. N. Bahcall and S. C. Frautschi, *ibid.* **29B**, 623 (1969).
23. J. N. Bahcall, N. Cabibbo, A. Yahil, *Phys. Rev. Lett.* **28**, 316 (1972).
24. Research sponsored in part by the National Science Foundation (grant NSF GP-40768X) and in part by the Energy Research and Development Administration.

Reprinted from SCIENCE
23 January 1976, Volume 191, pp. 264-267